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Study on the Operation Mechanism and Effect of the Yellow River Water and Sediment Regulation System

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Abstract: In order to scientifically deal with the problems of less water and more sediment in the Yellow River and the uncoordinated relationship between water and sediment, it is necessary to establish a perfect water and sediment regulation system. Through the calculation of the sediment transport capacity of the Yellow River and the application of the water and sediment regulation system, it is found that the sediment transport efficiency of the Yellow River will increase with the increase of water flow, and there will be an obvious inflection point near the flat discharge. The joint regulation of the backbone reservoir group can discharge the large discharge close to the minimum flat discharge of the downstream river, which improves the sediment transport capacity of the river and alleviates the problem of sediment deposition. In this paper, through the introduction of the Yellow River water and sediment regulation project system, regulation indicators and mechanisms, the author discusses in detail the Yellow River water and sediment regulation scheme and its operation effect, hoping to provide help promote the improvement of the Yellow River governance effect.

Keywords: Yellow River; Water and sediment regulation; Regulatory indicators; Regulatory mechanism; Operation effect

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1. Introduction

The Yellow River is the mother river of China. It has watered the vast central plains, raised the Chinese people, cultivated the great Chinese national spirit, and created a splendid Chinese culture. Therefore, paying attention to the ecological protection of the Yellow River basin, strengthening the regulation of reservoirs, coordinating the water sediment relationship of the Yellow River, and ensuring the flood control safety and water supply safety of the Yellow River have always been issues of widespread concern to the people of the whole Yellow River Basin. For a long time, the problems of less water and more sediment and the uncoordinated relationship between water and sediment have been the main problems restricting the economic development of the Yellow River basin. In order to thoroughly improve this situation, we must build a perfect water and sediment regulation system and operation mechanism of the Yellow River, reduce the risk of bank breach caused by river sediment deposition by increasing water, reducing sediment, and regulating water and sediment, so as to ensure the long-term stability of the Yellow River, ensure the safety of production and life of the people downstream, and promote the high-quality development of the whole basin. In the early 1980s, in combination with the Xiaolangdi water control project, theoretical research on the variation law of water and sediment and the regulation of water and sediment in the Yellow

River were carried out, and demonstrated the key technologies such as the initial operating water level, regulating flow and regulating storage capacity of the Xiaolangdi reservoir. However, the research results show that this water and sediment control system cannot achieve the ideal goal of coordinating the water and sediment relationship. Therefore, in the context of the development of the new era, the Yellow River water and sediment control work should be combined with the operation indicators of reservoirs, through the accurate analysis of the operation mechanism of the water and sediment control system and the impact of the coordination degree of the Yellow River water and sediment relationship on the Yellow River trough section and reservoirs, so as to build a more perfect Yellow River water and sediment control system and operation mechanism, to ensure the best scouring and silting effect of the Yellow River reservoir and river channel, and to effectively promote the high quality of the Yellow River basin.

2. Water and sediment regulation engineering system of the Yellow River

The Yellow River water and sediment regulation project system is mainly built around Longyangxia, Liujiaxia, Heishanxia, Qikou, Guxian, Sanmenxia, Xiaolangdi and other key water conservancy hubs, and Luhun, Guxian, Hekou village, Dongzhuang reservoirs in the main stream and the tributaries of Haibowan and Wanjiazhai reservoirs. The project system is shown in **Figure 1**.

Figure 1. Water and sediment regulation engineering system of the Yellow River

The water and sediment regulation engineering system of the Yellow River mainly includes two key parts: the upstream regulation subsystem and the midstream regulation subsystem. Among them, the upstream regulation subsystem includes Longyangxia, Liujiaxia, Heishanxia reservoir, and so on. The main regulation indicators are to regulate water volume and optimize the regulation of water resources, so as to meet the requirements of upstream ice cream prevention, flood control and silt reduction to the greatest extent. In the whole Yellow River water differential regulation subsystem, Qikou, Guxian, Sanmenxia and Xiaolangdi reservoirs are the main bodies, which plays a decisive role in improving flood, sediment control, water diversion, coordinating the relationship between water and sediment and optimizing the water resources of the Yellow River. Among the key projects to be inspected, Dongzhuang water control project is the most important, which is expected to be completed in 2025; Guxian Water Control Project has passed the review and is planned to start construction in 2030; Heishan Gorge and Qikou are currently in the preliminary demonstration stage of the project.

3. Water and sediment regulation index and mechanism of the Yellow River

3.1. Control indicators

The regulation of water and sediment in the Yellow River mainly includes the function index of sediment transport and flood discharge in the river, the safety index of flood control and ice prevention in the Yellow River, and the index of optimal allocation of water resources. It is the basic parameter to ensure the stable operation of the regulation system of water and sediment in the Yellow River. China has a long history of research on the water and sand control of the Yellow River, especially in the research on reducing the siltation of the river. Scholars An Guihua, Lu Jun et al. [1], based on the analysis of flood data measured in the Ningjiang-Mongolia Reach, concluded that the basic regulated flow rate for maintaining and restoring the middle water channel in the Ningjiang-Mongolia Reach was 2.5×10^3–$3.0 \times 10^3 m^3/s$, and the corresponding regulated water amount was 3.2 -3.9 billion m^3.Scholars Hu Chunhong, Liu Jixiang et al. [2,3] analyzed the flood data measured in the lower Reaches of the Yellow River, and pointed out that the effectively regulated flow should be more than $2.6\times10^3 m^3/s$ for sediment transport and water restoration and maintenance in the lower Reaches of the Yellow River. Among them, when the scour efficiency is the highest, the regulated flow is 3.0×10^3- $4.0\times10^3 m^3/s$, and the corresponding regulated water is 1.5−1.7 billion m^3.

In this study, the reasonable regulation index of river sediment transport and flood discharge is obtained through the calculation of river sediment transport capacity formula (formula 1).The average depth of riverbed is closely related to water flow. Taking $h = \alpha Q^{\beta}$ and $U = \frac{1}{n} h^{\frac{2}{3}} J^{\frac{1}{2}}$ into the sediment carrying capacity formula of water flow $S* = K\left(\frac{U^3}{gh\omega}\right)^m$, the formula of river sediment carrying capacity can be obtained:

$$S* = K \alpha^m Q^{\beta m} \left(\frac{J^{3/2}}{g\omega n^3}\right)^m \qquad (1)$$

Where,

H−average water depth of river channel (m);

Q−flow (m^3/s);

U−average flow velocity of section (m/s);

S−flow sediment transport capacity (kg/m3);

N−roughness;

J−hydraulic gradient;

G−gravitational acceleration (m/s^2);

Ω−average sedimentation velocity of sediment, (m/s);

K. M−sediment carrying capacity coefficient and index;

α, β−Coefficient

When water flows through the main channel of the lower reaches of the Yellow River, the sediment transport capacity of the rive− will increase with the increase of water flow; When water flows through the floodplain, due to the high roughness of the floodplain, the flow radius of the river section decreases, and the sediment transport capacity of the river channel also decreases. Therefore, there is often an obvious inflection point in the sediment transport capacity of the river channel in the flat area [4]. In the whole water and sediment regulation system of the Yellow River, the minimum flat discharge of the river is located in the Gaocun Aishan river section. Therefore, in order to effectively improve the sediment transport capacity into the sea and reduce the risk of river siltation during the operation of the water and sediment regulation system, it is necessary to create the flow passage conditions closest to the flat discharge on the premise of fully considering the flood control requirements of the region [5].

3.2. Regulation mechanism

Because of the great difference between topographic and climatic conditions in the whole Yellow River basin, the Yellow River presents the characteristics of different sources of water and sediment and great interannual variation of water and sediment.The water volume of the Yellow River mainly comes from the upper Hekou Town, and the sediment source of the Yellow River is concentrated in the Hekou town Longmen interval and Longmen Sanmenxia interval. Therefore, the regulation subsystem of the upper reaches of the Yellow River should mainly regulate the water volume; the Yellow River red oil regulation subsystem should focus on flood and sediment regulation, and build a mutual cooperation mechanism between the middle and upper reaches of the regulation subsystem, which can achieve the goal of coordinated regulation of the Yellow River water sediment relationship [6].

(1) Upstream regulation mechanism

The total drainage area above Hekou town is $3.8 \times 105km^2$ is the main source of the water volume of the Yellow River, accounting for 65% of the total water volume of the whole basin. Therefore, the regulation objectives of the basins above Hekou town have been water volume regulation, mainly to supplement the dry season with abundant water, improve the supply capacity of water resources and the production efficiency of cascade hydropower stations.

Since the South-to-North Water Transfer Project was put into operation, the inflow of water from the west line into the Yellow River has become the main way of water regulation in the upper reaches of the Yellow River. The completion and operation of Heishanxia reservoir has played an anti-regulating role in the discharge flow under the upstream cascade hydropower stations. Therefore, in the operation process of the water and sediment regulation system, the non-flood season water volume should be adjusted to the flood season in combination with ice control scheduling, creating a 2.5×10^3–3×10^3 m^3/s flood discharge, in order to minimize the adverse impact of the large storage volume of Longyangxia and Liujiaxia Reservoirs on the Ningmeng river section in the flood season realize the scientific coordination of the water sediment relationship in the Ningmeng river section, and curb the occurrence of suspended rivers in the Ningmeng river section [7].

(2) Midstream regulation mechanism

The flood and sediment entering the lower reaches of the Yellow River mainly come from Hekou town-Sanmenxia section in the middle reaches of the Yellow River, and the annual water volume accounts for only 35.6% of the total water volume of the whole basin, while the annual sediment volume accounts for nearly 90% [8]. Therefore, the work of water and sediment regulation in the middle reaches of the Yellow River should focus on reducing peak discharge, combined sediment detention and water and sediment regulation. This operating mechanism can not only reduce the risk of river siltation, but also moderately restore the flood and sediment transport capacity of the river channel.

At present, in the regulation and control of water and sediment in the middle reaches of the Yellow River, water and sediment regulation is mainly carried out around Xiaolangdi reservoir, and the discharge capacity of the main channel of the river is improved under the timely operation of Wanjiazhai, Sanmenxia Reservoir and their tributary reservoirs, so as to ensure that the disharmony between water and sediment in the downstream river is effectively improved [9].

(3) Joint application mechanism of middle and upper reaches

Based on the analysis of the characteristics of the water and sediment heterogenesis of the Yellow River, the water and sediment regulation work of the Yellow River should be combined with the application of the upstream regulation system and the midstream regulation system. In the process of upstream regulation and control, it is necessary to focus on the regulation and control of water discharge in flood season, so as to provide sufficient hydraulic conditions for the coordination of water sediment relations in the middle reaches; The regulation and control of the middle reaches should focus on shaping the sediment transport volume of the flat beach, so as to minimize the siltation of the flat beach out of the riverbed.

During the specific application of the joint mechanism of the middle and upper reaches, the pre-discharge of Xiaolangdi reservoir is often carried out in combination with the flood evolution, so as to reserve enough storage capacity for the flood season, and ensure the over capacity of the reservoir in case of severe rainstorm. At the same time, by docking with the discharge flow of the upper reaches, it provides sufficient power for the water and sediment regulation of the middle and lower reaches of the reservoir, so as to achieve the best dredging effect of the reservoir and the river [10].

4. Scheme and effect of water and sediment regulation in the Yellow River

4.1. Water and sediment conditions

Relevant research results show that there are two main reasons for the great changes in moderate runoff and sediment volume, one is the influence of natural climate factors, and the other is the influence of human activities. This paper analyzes the effect of water and sediment regulation based on the sediment inflow of 800 million tons in the middle reaches of the Yellow River. Based on the calculation of the annual average water and sediment yield during the period of 1988−1997 + (1959-2008) × 3, the accurate results of the annual average water and sediment yield of 27.08 billion m^3, 796 million t and 29.4kg/m^3 were obtained.

4.2. Calculation method

The actual operation effect of the water and sediment regulation system of the Yellow River can be clarified through the analysis of the siltation amount and the coordination degree of water and sediment relationship in the lower reaches of the Yellow River. Among them, for the calculation of the expected volume of the lower Yellow River, the joint regulation model of reservoir and river sediment is used, and the coordination of water sediment relationship is queried through the coordination degree table of water sediment relationship [11].

(1) Combined regulation model of reservoir and river sediment

The joint mediation model of reservoir and river sediment mainly includes reservoir regulation and sediment scouring and silting module. The main function of the reservoir regulation module is to generate reservoir regulation instructions in combination with the different sediment scouring and silting states of the reservoir and the downstream channel, which in turn provides the boundary conditions for flow calculation for the sediment scouring and silting module [12].The sediment scouring and silting module is mainly composed of two parts: reservoir sediment scouring and silting and river sediment scouring and silting, both of which are calculated by one-dimensional hydrodynamic models (flow continuity equation and flow motion equation), which is shown below:

$$B\frac{\partial z}{\partial t}+\frac{\partial Q}{\partial x}=qt \tag{2}$$

$$\frac{\partial Z}{\partial t}+2\frac{Q}{A}\frac{\partial Q}{\partial x}-\frac{BQ^2}{A^2}\frac{\partial z}{\partial x}-\frac{Q^2}{A^2}\frac{\partial A}{\partial x}\Big|_Z=-gA\frac{\partial z}{\partial x}-\frac{gn^2|Q|Q}{A(\frac{A}{B})^{\frac{4}{3}}} \quad (3)$$

The suspended sediment is divided into M groups, and the sediment concentration of K groups is expressed by Sk. The unbalanced sediment transport equation and riverbed deformation equation can be obtained through equations (4) and (5):

$$\frac{\partial (AS_k)}{\partial t}+\frac{\partial QS_k}{\partial x}=-\alpha\ \omega_k B(S_k-S_{*k}) \quad (4)$$

$$\gamma'\frac{\partial A}{\partial t}=\sum_{k=1}^{M}\alpha\omega_k B(S_k-S_{*k}) \quad (5)$$

Where,
X−coordinate along the flow direction, m;
T−time, s;
z− water level height, m;
A − cross section water passing area, m²;
B−river width, m;
QL−inflow (outflow) flow per unit time and river length, m²/ s;
A−recovery saturation coefficient;
ω_K−settling velocity of sediment particles in Group K, m/s;
S_k−sediment carrying capacity of Group K, kg/m^3;
γ'−dry bulk density of sediment, kg/m^3.

The governing equation of the mathematical model is discretized by finite volume method, and the coupling relationship between flow and water level is processed by simple algorithm based on staggered grid. The model has been tested by many measured data of the Xiaobei main stream of the Yellow River, Sanmenxia reservoir, Xiaolangdi reservoir, the lower reaches of the Yellow River and the estuary of the Yellow River, and can accurately reflect the characteristics of water and sediment transport and sediment erosion in the study area.

(2) Coordination degree of water sediment relationship

The lower reaches of the Yellow River have the lowest slope and the most serious sediment deposition.Relevant scholars have proposed that the long-term non silt or silt deposition process in the main channel of the lower Yellow River is the basis for maintaining the harmonious relationship between water and sediment of the Yellow River, and defined the coordination degree of water and sediment relationship [13].The calculation formula of water sediment coordination relationship is shown in equation (6):

$$Cun(i)=\frac{\xi_i}{\xi_T} \quad (6)$$

Where,
Cun(i) − coordination degree of water sediment relationship;
i − sediment inflow coefficient of different water and sediment source areas of the Yellow River;
ξ_T − critical sediment inflow coefficient of non-siltation or slight siltation in the lower reaches of the Yellow River.

According to formula (1), divide the calculated sediment transport efficiency by the flow velocity, that is, the ratio of critical sediment concentration to flow velocity. If the sediment inflow coefficient is greater than the critical sediment inflow coefficient, that is, Cun(i) > 1, it indicates that the river channel is in a siltation state and the water sediment relationship is not harmonious. If the coefficient is less than the critical cement sand coefficient, that is, Cun(i) < 1, the river channel is in a scouring state, and the water sediment relationship is coordinated. The smaller the Cun(i) is, the higher the coordination degree of water sediment relationship is [14].

4.3. Regulation scheme

In order to study the operation effect of the Yellow River water and sediment regulation system, the five schemes in **Table 1** are combined according to the time when the backbone projects are put into operation.

Table 1. Application scheme of Yellow River water and sediment regulation system project

Working condition	Programme	Combined application scheme
1	Xiaolangdi Project	Longyangxia + Liujiaxia + Haibowan + Wanjiazhai + Sanmenxia + Xiaolangdi + Luhun + Guxian + Hekou Village
2	Xiaolangdi + Guxian (2030) + Dongzhuang (2025)	Longyangxia + Liujiaxia + Haibowan + Wanjiazhai + Guxian + Sanmenxia + Xiaolangdi + Luhun + Guxian County + Hekou village + Dongzhuang
3	Xiaolangdi + Guxian + Dongzhuang + Heishanxia (2035)	Longyangxia + Liujiaxia + Heishanxia + Haibowan + Wanjiazhai + Guxian + Sanmenxia + Xiaolangdi + Luhun + Guxian County + Hekou village + Dongzhuang
4	Xiaolangdi + Guxian + Dongzhuang + Heishanxia + Qikou (2035)	Longyangxia + Liujiaxia + Heishanxia + Haibowan + Wanjiazhai + Guxian + Qikou + Sanmenxia + Xiaolangdi + Luhun + Guxian County + Hekou village + Dongzhuang
5	Xiaolangdi + Guxian + Dongzhuang + Heishanxia + Qikou + West Line Phase I Project (2035)	Longyangxia + West Line Phase I + Liujiaxia + Heishan Gorge + Haibowan + Wanjiazhai + Guxian + Qikou + Sanmenxia + Xiaolangdi + Luhun + Guxian County + Hekou village + Dongzhuang

4.4. Regulation effect

The numerical model is used to calculate the scouring and silting changes of the downstream channel of different engineering application schemes under the condition of 800million tons of sediment coming from the Yellow River in the future. Equation (6) is used to calculate the coordination degree of water sediment relationship [15]. The starting year is 2020, and the calculation results are shown in **Table 2**.

Table 2. Regulation effect of key water and sediment regulation projects of the Yellow River on water and sediment entering the downstream (calculation period: 160 years)

Working condition	Programme	Water volume entering downstream / 100 million M^3		Sediment entering downstream / 100 million T		Coordination degree of water sediment relationship			Annual average sediment reduction of downstream channel after sediment detention period / 100 million t
		Flood season	Year	Flood season	Year	During sediment detention period	Normal operation period	Multi-year average	
1	Xiaolangdi Project	143.5	277.3	6.9	6.9	0.9	1.4	1.3	-
2	Xiaolangdi + Guxian + Dongzhuang	129.9	264.7	5.8	5.9	0.8	1.3	1.1	0.5
3	Xiaolangdi + Guxian + Dongzhuang + Heishanxia	154.1	262.6	5.7	5.8	0.7	1.2	1.1	0.8
4	Xiaolangdi + Guxian + Dongzhuang + Heishanxia + Qikou	155.7	262.6	4.9	5.0	0.7	1.2	1.0	1.3
5	Xiaolangdi + Guxian + Dongzhuang + Heishanxia + Qikou + West Line Phase I Project	167.3	279.4	5.1	5.2	0.7	1.2	0.9	1.5

5. Conclusion

In conclusion, the governance of the Yellow River Basin still faces great challenges, and the protection of ecological environment and economic development need to be coordinated and followed up. Only by analyzing the disharmonious relationship between water and sediment in the Yellow River Basin at this stage, and constantly improving the basin planning, basin protection, basin governance and other aspects, can we better make fruitful contributions to the high-quality development of the basin economy and help realize the dream of China's rejuvenation.

Disclosure statement

The authors declare no conflict of interest.

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